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A REVIEW OF AEROBIC BIOCELL RESEARCH AND TECHNOLOGY

Prepared for the Aerobic Process Subcommittee
of the Solid Waste Association of North America
Bioreactor Committee

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Introduction

Information on aerobic degradation of Municipal Solid Waste (MSW) comes from actual operations of full-scale, pilot-scale, and lab-scale tests. Other areas such as composting facilities and leachate treatment plants give related data that can be useful in developing the aerobic biocell system. The modern implementation of the aerobic biocell is predicated on maximizing degradation rates with the potential for landfill reclamation. In the literature, it was found that France, Spain, Japan and the United States have working aerobic landfill systems in place. Some useful information also comes from work done in Europe on the effects of mechanically and biologically treating MSW prior to landfilling. The information that is required for further investment in aerobic systems can include: moisture levels, aeration rates, and temperature control for optimum stabilization, methane reduction,reduction of non-methane organic compounds (NMOCs), odor reduction, leachate volume and strength, settlement increases, and cost-benefit analysis.

The aerobic biocell concept seems to be able to fulfill environmental needs, as well as economic needs. In the United States the most immediate issue is how well the ABS (aerobic biocell system) does in meeting the guidelines as presented in the EPA's "Requirements for the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills".

Aerobic Biocell

The Japanese have been using semi-aerobic, recirculatory semi-aerobic, and aerobic landfills for a number of years. These types of landfill technologies are described in Hanashima, Matsufuji et al. (1989). Other descriptions of the aerobic biocell can be found in Johnson and Baker (1999), Stessel and Murphy (1992), Hudgins and Harper (1998), and Stessel and Murphy (1994). The aerobic landfill that is used in Spain and in France is of a different type: there is no leachate recirculation, nor forced aeration. The waste is, instead, placed in thin layers and compacted with a sheeps-foot compactor (Deusto, Lopez et al. 1998), (Dessaulx 1987). As for the leachate collection and recirculation Oweis and Khera (1998) provides a good description of what would be needed.

Optimal conditions for biocell operation.

Moisture levels ought to be higher than typical composting operations. Levels from 45%-80% are found throughout the literature. The ability to control the moisture levels within the cell is essential for optimizing microbial activity. Leachate recirculation alone will not be sufficient, so the addition of other water sources must be considered. In Johnson and Baker (1999) the injection of approximately 100,000 gallons of water and leachate was used for the first 4 weeks. In the end, some 1,800,000 gallons of water were pumped into the cell, or around 6,800 gallons per day. This corresponded to average moisture contents between 24 and 55% (wet weight basis)(Johnson and Baker 1999).

Aeration rates have an important role to play in keeping temperatures at proper levels, and reducing methane and odors normally associated with MSW landfills. The most useful studies for design and operation come from

(Keener, Elwell et al. 1998) and (Keener, Hansen et al. 1997), where kinetic data from 38 pilot studies are summarized, and airflow requirements are modeled. The influence of aeration rate and initial moisture content on rates and extent of degradation was also presented in (VanderGheynst, Gossett et al. 1997). A hybrid, positive/negative, aeration system was described by Sesay, Lasaridi et al. (1998) to decrease moisture loss and distribute oxygen more evenly. **Table 1** shows the range of airflow rates that were used in the literature.

Temperature data are also presented from many sources. Typical operating temperatures range from 38 to 60 degrees Celsius. Peaks in temperature over 60°C lead to "crashes" of the thermophilic microbial populations, resulting in incomplete degradation. With these optimal high temperatures pathogen destruction takes place. Most pathogenic organisms are dead after one hour at this temperature. See **Table 2** for pathogen destruction data.

Table 1 Optimal aeration rates, moisture levels and temperatures

Reference	Aeration rate (L/min·kg)	Moisture (%)	Temperature (°C)
(Johnson and Baker 1999)		24-55 w/depth	ave. >38
(VanderGheynst, Cogan et al. 1998)	0.65-0.83	45-60	peak 43-60
(Brown, Thomas et al. 1997)	0.47-0.70	50	
(Keener, Elwell et al. 1998)	0.347-0.972	50-60	35-60
(VanderGheynst, Gossett et al. 1997)	0.06-0.94	45	55
(Murphy, Jones et al. 1995)	420 L/min (As given)	80	
(Matsufuji, Hanashima et al. 1993)	0.593	53	
(Boni, Delle Site et al. 1997)	0.04-0.06 for 90 days	36	peak 55
(Stessel and Murphy 1992)	40,000 m^3 of air/ m^3 of water applied	75	
(Hudgins and Harper 1998)		>50	40-60
(Leikam, Heyer et al. 1997)	0.12 weekly		
(Kayhanian and Tchobanoglous 1993)	3.96 wet mass		
(Anderson 1990)	0.42-1.25	50-70	
(Keener, Hansen et al. 1997)	0.53	45-52	55-60
(Ma, Zhang et al. 1997)	0.85-1.7 L/min·m^3	60	50-60

Table 2 Mortality of organisms in MSW (Dessaulx 1987)

Salmonella Typhosa	No development over 46°C - Dead in 30 min. at 55-60°C
Escherichia Coli	Dead in one hour at 55°C and in 20 min. at 60°C
Trichinella Spiralis (larva)	Quickly killed at 55°C, instantaneously at 60°C
Streptococcus Pyogenes	Dead in 10 min. at 54°C
Microbacterium Tuberculosis	Dead in 15 to 20 min. at 60°C
Corynebacterium Dipteriae	Dead in 45 minutes at 55°C

With high moisture greatly reduce the probability of landfill fires,and increase degradation and final bulk densities. Periodic landfill fires in aerobic cells occurred in studies where initial waste moisture was 44%, and water additions were limited (Merz and Stone 1970). Control of water volume and flow is important, and data on leachate recirculation and water addition is presented in Johnson and Baker (1999) and Hanashima (1989).

By being able to manipulate the aeration levels aerobic and anaerobic conditions can be created, similar to wastewater treatment plants, so that the recirculated leachate can be treated, and heavy metals can be stabilized into the clay liner (Pohland's work). Sequencing of anaerobic and aerobic conditions is described by Kayhanian and Tchobanoglous (1993) and Boni, Delle Site et al. (1997). Their aim was to maximize methane production and decrease retention time for full stabilization.

<u>Gases</u>

Methane reduction has been studied in full-scale aerobic landfills, in-vessel composting systems, lab-scale lysimeters, and by placing composted material in normal anaerobic landfills. Generally, in terms of methane emission reductions, recovery and utilization of landfill gas in anaerobic systems gives similar results to aerobic biocells (50-90% reductions)(EPA, 1999).

Table 3 Methane emission reductions from different aerobic processes

Type	Reference	Reduction
Field	(Johnson and Baker 1999)	From 46% to 10% CH_4 in emission
	(Matsufuji, Hanashima et al. 1993)	*See tables 4 and 5
	(Hudgins and Harper 1998)	Methane reduced by 50% to 90% for 80% of the points. Concentrations remained below 15%(v/v)
(In-situ remediation)	(Leikam, Heyer et al. 1997)	During aeration phase the methane concentration drops to zero. After days without aeration, methane concentration ≤ 10%
Pre-treated	(West, Brown et al. 1998)	77%
	(Muller, Fricke et al. 1998)	95%
Lab-scale	(VanderGheynst, Cogan et al. 1998)	>89% reduction in CH_4 at 60% moisture, 0.83 L/min·kg aeration
Windrow	(Hellmann, Zelles et al. 1997)	Highest CH_4 emission rate - 1000 mg/ton·hr

Even when pockets of anaerobic activity take place and methane is produced, the humic material produced by degradation in the matrix, and soil layers in the cap can oxidize the methane to an even lower ambient concentration at the surface. The kinetics of methane oxidation in landfill cover soils is investigated in papers by DeVisscher, Thomas et al. (1999) and Bogner, Spokas et al. (1997).

Odor reduction
In pilot-scale studies, strong NH_3 and H_2S odors associated with conventional landfill operations were reported as "successfully eliminated"(Johnson and Baker 1999), as well as, "minimal throughout the aerobic landfill operations"(Hudgins and Harper 1998). Using synthetic food waste and biosolids to assess the effects of aeration rate and moisture content on emissions of odorous organosulfur emissions (VanderGheynst, Cogan et al. 1998) showed a decrease with increasing aeration.

Table 4 Total amount of greenhouse effect gases for different landfill types

Landfill type	CO_2 during 10 yrs (10^6L)	CH_4 during 10 yrs (10^6L)	Amount of CH_4 into CO_2 (10^6L)	Total amount of gas (10^6)	Ratio of each type to anaerobic
Anaerobic	132,370	397,110	11,913,300	12,045,670	1
Semi-Aerobic	227,994	170,996	5,129,880	5,357,874	0.44
Recirculating Semi-aerobic	286,838	88,255	2,647,650	2,934,488	0.24
Aerobic	350,781	50.8	1,523,130	1,873,911	0.16

(Matsufuji, Hanashima et al. 1993)

Table 5 Proportion of CO_2 to CH_4 generated by landfill type

Landfill type:	CO_2 (%)	CH_4 (%)
Anaerobic	50	50
Semi-aerobic	80	20
Recirculating semi-aerobic	90	10
Aerobic	95	5

(Matsufuji, Hanashima et al. 1993)

CO_2 emissions will increase as CH_4 and NMOCs decrease, however, since CH_4 is 35 times more potent of a GHG than CO_2, net GHG impacts will decrease. Research on NMOC emissions from landfills is limited. Laboratory and field investigations on the ability of the aerobic landfill to prevent the production of NMOCs are needed.

VOCs
The aerobic biocells in Columbia County, Georgia have demonstrated VOCs in leachate reduced by between 50 to 90%. Total VOC concentrations in many of the vapor samples were less than 1 ppm (Hudgins and Harper 1998). As no comprehensive data are available from aerobic biocell operations, literature from the composting world was again consulted. The other literature that relates to this area either deals with emissions at composting facilities, or with laboratory in-vessel composters. The facilities sampled gave total VOC concentrations that were highest in the active composting region, and second highest in the tipping area. **Table 6a** shows average gas concentrations of some of the highest samples, while **Table 6b** shows volatilization and biodegradation levels for some compounds.

Perhaps the most informative study used in-vessel composters to evaluate the fate of four VOCs (benzene, carbon tetrachloride, dichlorobenzene and xylene) and two pesticides (Captan and Lindane). The results showed concentrations below detection limits after 1 week of composting for the VOCs, and the two pesticides were reduced by 80% and 42%, respectively, after five weeks (Brown, Thomas et al. 1997).

Table 6a Average concentration of VOCs at composting facility

Compound	Tipping area[a] ($\mu g/m^3$)	Active composting[a] ($\mu g/m^3$)
trichlorofluoromethane	12,600	64,300
acetone	6,100	9,200
2-butanone	25,500	4,300
1,1,1-tricloroethane	1,200	1,500
toluene	8,800	3,900
ethylbenzene	38,100	3,100
m,o-xylene	2,600	520
methyl ethyl ketone		12,000[b]
methylene chloride		5,000[b]

[a] (Eitzer 1995)
[b] (Kim, Park et al. 1995)

Table 6b Estimated percent removal efficiencies

VOC	Volatilization		Biodegradation	Residuals
Chloroform	74.3		25.7	0
Ethyl benzene	0		93.8	6.2
Methylene chloride	95.5		4.5	0
TCE	>0		>0	>0
Toulene	12.4	20 (Spongberg, Thomas et al. 1996)	87.4	0.2

(Kim, Park et al. 1995)

Degradation of PAHs under bench-scale compost conditions was investigated by Potter, Glaser et al. (1999). In this study starting concentrations of total PAHs ranged from 1606 to 4445 mg/kg, and final concentrations ranged from 888 to 1556 mg/kg in the in-vessel composting reactors, however there was no apparent decrease in concentrations of 5 and 6-ring PAHs during the first 12 weeks of composting (Potter, Glaser et al. 1999).

Nitrogen fluxes, whether in gas or liquid, are dealt with in Burton and Watson-Craik (1998), Soliva, Giro et al. (1993), Onay and Pohland (1998), and Welander (1998). Burton and Onay deal specifically with ammonia nitrogen, denitrification, nitrification and landfills/bioreactors. Whereas Soliva's study is on nitrogen loss at composting facilities, Welander's study is on treatment of leachate ex-situ. These studies show the advantages of working using aerobic bacteria when high nitrogen levels are present.

Nitrous oxide (N_2O) is the third-most-common greenhouse gas. While it is produced in the aggregate at only 2.4% of the rate of CH_4, its global warming potential (GWP) is five times that of CH_4. N_2O is produced under microaerobic conditions during the processing of organic wastes with high moisture (Czepiel, Douglas et al. 1996). The emission potential from composting municipal sludge is 0.7 g of N_2O/kg dry sludge. In windrow composting, emission rates of N_2O reached 50-100 mg/tons·hr (Hellmann, Zelles et al. 1997). Bacterial strains from activated sludge from waste water treatment basins were studied by Frette, Gejlsbjerg et al. (1997). It was found that one strain (strain 1 of the *Pseudomonas nautica*) produced large amounts of N_2O from aerobic denitrification (Frette, Gejlsbjerg et al. 1997). It was also found that increased N_2O emissions are often observed under moderate O_2 concentrations (5-15%),when relatively low CH_4 emissions are measured (Tsujimoto, Masuda et al. 1994). It was suggested by Hellmann, Zelles et al. (1997) and Tsujimoto, Masuda et al. (1994) that there is an inverse relationship between N_2O emissions and CH_4 production.

Table 7 Nutrients in yard waste composts produced using different oxygenation rates

Oxygenation rate	pH	Total NO_2 (mg/kg)	Total NH_4 (mg/kg)
10 ml O_2/min	8.6	103	189
1 ml O_2/min	7.2	200	2798
0.1 ml O_2/min	4.9	217	959
0 ml O_2/min	4.8	182	1195

(Michel 1999)

Leachate Characteristics

Leachate collection, recirculation, and make-up water addition systems are required for the ABS to be successful. By operating a landfill as an aerobic biocell there is decreased solubility of metals leading to lower migration via leachate, as well as a net reduction in leachate volume and strength. Studies of leachate from aerobic processes measure pH, TKN, BOD, COD, and VOCs. In operational aerobic landfills the level of leachate treatment within the waste cell is impressive. For most studies in this search the pH levels in leachate from aerobic systems remained within the neutral range. In the Japanese full-scale landfill experience monthly BOD concentrations show that minimal BOD levels are attained within 1-1.5 years with aerobic and semi-aerobic landfills, while anaerobic-type fills remain consistantly high. The COD concentration of leachate in the semi-aerobic type was lower by 1/10-1/5 by comparison to the anaerobic type (Hanashima, Matsufuji et al. 1989). In every series involving comparisons, the leachate quality is improved more quickly in aerobic biocells with leachate recirculation, than in anaerobic or in non-recirculating aerobic ones. **Table 8** shows a summary of some leachate characteristics from different types of aerobic treatments.

Table 9 shows the volume reductions that can be expected from running an aerobic biocell. In the Spanish aerobic system, which is not an aerobic biocell design, leachate generation was reduced by 78% in comparison to anaerobic systems at the same facility. The implications mean savings on treatment costs and lessened risk of ground water contamination.

In-situ treatment of landfill leachate in old sites adds to the attractiveness of the aerobic biocell concept. Studies on in-situ stabilization provide useful information for development of the ABS. Aeration rates and the effect on leachate is given in (Leikam, Heyer et al. 1997).

Table 8 Leachate characteristics from aerobically degraded waste

Reference	type	BOD	COD	pH
(Schneider and Rump 1982)	Lab-scale	10-100 mg/L	1,000-3,000 mg/L	
(Muller, Fricke et al. 1998)	Pretreatment	BOD/COD ratio 0.13-0.19 after 4 months	0.05-0.1 after 6 months	
(Boni, Delle Site et al. 1997)	Lab-scale		1,800 mg/L at 90 d	8 to 9
(Stessel and Murphy 1992)	Lab-scale		1,000 mg/L at 20 d	7.5 to 8.5
(Hudgins and Harper 1998)	Pilot-scale	Reduced by 70%		
(Hanashima, Matsufuji et al. 1989)	Recirculatory semi-aerobic	Reduced 83% in 100 days. Up to 98% in 2 years.	settle between 500 and 1,000 mg/L	7 to 8
(Leikam, Heyer et al. 1997)	In-situ stabilized	low	low	6.8 to 7.6
(Onay and Pohland 1998)	Lab-scale		93% reduction	6.3 to 7.1

Table 9 Leachate volume reduction

Reference	Reduction
(Hudgins and Harper 1998)	86%
(Deusto. Lopez et al. 1998)	78%

Solids

Decomposition rates and measures of stability are of great importance to ABS operators who are looking to reclaim the cell. An important article to be considered is (Keener, Elwell et al. 1998). This article summarizes kinetic data from 38 pilot studies on municipal solid waste, biosolids, food waste, poultry manure, and separated dairy waste and describes how to evaluate the kinetic parameters. These were then used to calculate airflow requirements, time blowers can be off, and time for water addition.Composting times used in the analysis ranged from 14 days for some sludge mixes to 54 days for MSW. With data on composting times from many different operations it is necessary to develop analytical expressions that model the compost behavior. One such expression is a reaction rate constant, *k*, the rate of disappearance of dry matter per unit of compostable dry matter (day^{-1}). It is a function of substrate compounds, microbial populations, temperature, moisture content, surface area exposed, interstitial atmosphere (Keener, Elwell et al. 1998). **Table 10** shows two papers' *k* values for different conditions.

More often than giving k-values for decomposition rates, the literature gives composting cycle times. In actual biocell operations a fill-degrade-mine cycle might be anywhere from 2 years to 8 years. The Columbia County ABS ran for 21 months (Hudgins and Harper 1998), while the Live Oak ABS was partially mined after 7 months of operation (Johnson and Baker 1999). In the European aerobic landfill, cycle duration refers to the time between layer placement. Cycle duration of decomposition in a non-biocell-like, aerobic landfill varied between 23 and 59 days (Deusto, Lopez et al. 1998) in Spain and about 42 to 70 days (Dessaulx 1987) in France.

Table 10 Reaction rate constant for the composting of MSW

Variable parameter	Reaction rate constant k (day^{-1})[a]
Moisture content (%)	
45	0.053
60	0.180
75	0.095
C/N ratio	
15	0.12
20	0.13
30	0.17

Temp (°C)	Moisture (%)	C/N	k (day^{-1})[b]
45	61	46.8	0.051
62	61	46.8	0.083
55	56.4	33.2	0.024
60	39.7	31.1	0.032

[a] (Hamoda, Abu Qdais et al. 1998)
[b] (Keener, Elwell et al. 1998)

Measures of stability of waste from aerobic treatment vary. Assessing stability by temperature, or by settlement, are gross measures of stabilization. One technique that is gaining acceptance for determining the stability of composted MSW is Specific Oxygen Uptake Rate (SOUR), also called respiration activity . Aerated static piles with an initial SOUR value of 18.92 mgO_2/(g·hr) drop to between 1.81 and 1.37 MgO_2/(g·hr) after 51 days of positive and negative pressure aeration (Sesay, Lasaridi et al. 1998). The respiration activity fits nicely as an exponentially decreasing graph in lab studies. Reductions of SOUR to levels of 1.5-3 mgO^2/g·hr after five to six months of composting indicate stabilized waste, and constitute reductions of up to 98% from initial levels (Muller, Fricke et al. 1998).

Table 11 Various organic matter fractions during the composting of a MSW/sewage sludge mixture

Time (weeks)	Easily Biodegradable Fraction (%OM)	Cellulose (%dm)	Lignin (%dm)
0	19.7	12.7	6.8
1	19.9	12.6	6.0
4	19.2	9.7	8.2
9	14.7	7.1	7.1
23	10.0	3.0	5.6

(Muller 1998)

It was found in Murphy, Jones et al. (1995) that the level of cellulose degraded (mg/24hr·g dry wt. refuse) is significantly higher in aerobic lysimeters, than in anaerobic ones. The key parameter chosen was the cellulase activity. At the end of the 90[th] day of the test the aerobic lysimeter showed degradation rates of 2.5 mg/day·g, while the anaerobic lysimeter cellulase acyivity could not be detected (Murphy, Jones et al. 1995). Another study that dealt with lignocellulosic waste transformations was by Vinceslas-Akpa and Loquet (1997). **Table 11** gives results of a study of aerobic pre-treatment that was done by Muller (1998).

With reduction of odors and faster stability reclamation projects are more feasible. The waste volume can be reclaimed over a period of less than 5 years. Mined product data is given in Johnson and Baker (1999), Stessel and Murphy (1992), Hudgins and Harper (1998), Stessel and Murphy (1994), and Stessel and Murphy (1992). These are listed in **Table 12** along with comparison data from other landfill types.

Table 12 Settlement and Density data

Settlement:	Comments:
(Stessel and Murphy 1992) Settlement high of <u>36%</u>	Lab-scale lysimeters with shredded MSW and leachate recirculation for 70 days
(Hudgins and Harper 1998) Settlement high <u>10-12%</u>	Pilot-scale biocells without over- burden, non-shredded MSW with leachate recirculation for < 1 year
Density: Oweis & Khera (98) 810-1,080 lb/yd3 **1,215-1,620 lb/yd^3**	Typical Northeast U.S. active landfill MSW under good to excellent compaction
(Boni, Delle Site et al. 1997) **1,400 lb/yd^3**	Lab-scale plant, non-shredded waste with leachate recirculation, 40 days of aerobic pretreatment
(Deusto, Lopez et al. 1998) **1,835-2,020 lb/yd^3**	Full-scale aerobic landfilling in Spain, no cap, shredding prior
(Das and Keener 1997) Average: **2,295 lb/yd^3**	Lab-scale compression of biosolid compost. Initial moisture: 43-57% Stress applied: 0-43.2 kPa
Chang 93 Increase from 710 to **1,400 lb/yd^3**	In-place landfill densities of shredded MSW compared with no shredding
(Scrudato, Pagano et al. 1993) **> 1,510 lb/yd^3**	Pilot-scale Posi-Shell® stabilized placements. Shredded MSW with moisture addition while shredding and 3 months of aeration, then compaction.
(Heerenklage and Stegmann 1995) **1,500-2,350 lb/yd^3**	Mechanically and biologically pretreated MSW, measured after landfilling. Volume **reduced up to 60%** using combined pretreatment, compared with untreated.
(Collins 1991)	Observed that removal of recyclables from MSW stream followed by aerobic pretreatment of organic fraction can lead to landfill **reduction of 76%** compared with unsorted and untreated MSW.

Cost/Benefit Analysis

Costs associated with aerobic biocell operation are addressed in Keener, Hansen et al. (1997). Leikam, Heyer et al. (1997), Darragh (1997). Hudgins and Harper (1998), and Stessel and Murphy (1992). Stessel makes an estimate value savings to capital cost ratio of over 2:1 assuming an 8 year fill-degrade-mine cycle and a total life of 40 years (Stessel and Murphy 1992). In Georgia, it is believed that the technology of the ABS will pay for itself if it increases capacity of the 16-acre landfill by just 3%. This technology may have a furthur fiscal benefit if it reduces future liability costs from liner failure. Assuming settlement of 15% and compacted waste density of 1,300 lbs/yd^3 Hudgins estimates over $2.3 million additional revenue could be generated from a 1 million cubic yard fill (Hudgins and Harper 1998). Estimated savings data are shown in Table 13. Models for expressing variable costs, fan sizing, and fixed costs associated with composting facilities are presented in (Keener, Hansen et al. 1997).

Table 13 Estimates of cost benefits

	(Darragh 1997)[a]	(Hudgins and Harper 1998)
Recalimed landfill volume	$5,070,000	$2,300,000
Leachate Treatment savings	$175,000	$21,600/year
Post-closure sampling savings	$270,000	
Post-closure leachate treatment savings	$26,000	$222,000[b]
Total benefits	$5,541,000	$2,738,000

[a] based on 10 year life
[b] over 40 years

The bottom line is that the ABS will dramatically lower costs associated with leachate treatment, reduce post-closure liabilities, and extend the life of the facility.

Conclusion

Problems remaining to be studied:

- Relationship of leachate drainage, recirculation, and quality of solid waste.
- Optimum amount of leachate recirculated per day by kind of solid waste, including make-up fluid.
- Optimum method of leachate recirculation (continuous or intermittent), and distribution techniques.
- Effect of leachate aeration before recirculation on leachate quality.
- Chemical, physical and biological mechanisms influencing leachate quality.
- Nitrous oxide production conditions
- Clarification of the oxygen-cellulase activity relationship.
- Effect of anaerobic/aerobic shifts in operation for stripping heavy metals from the waste matrix.
- Development of process trains to best recover materials mined from aerobic biocells.

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